

## Supplementary Information

### Detailed Methods

#### *I - Lateral nutrient distribution*

##### *Terrestrial mammal lateral nutrient distribution*

Lateral nutrient distribution capacity was mathematically formulated and found to be strongly size dependent in two previous papers (1, 2). We now use this framework to calculate how the ability of land mammals and great whales to diffuse nutrients away from hotspots may have changed following the widespread extinctions of megafauna and hunting of whales. We estimate the total capability of animals to distribute nutrients both now, with the current IUCN species range maps and body mass, and in the past for the now extinct Pleistocene megafauna, using a dataset of the ranges and body masses of extinct megafauna (3). We estimate the total capability of animals to distribute nutrients both now, with the current IUCN species range maps and body mass, and in the past for the now extinct Pleistocene megafauna, using a dataset of the ranges and body masses of extinct megafauna (3). All species with occurrence records from within the last 130,000 years (Late Pleistocene and Holocene) were included. The taxonomy for extinct species followed Faurby and Svenning (3). The present-natural distribution for all extant and extinct species were estimated, i.e., maps of where these species would have occurred today under natural conditions in the absence of human-driven extinctions and range changes. This dataset is based on historical information when available or alternatively based on a method similar to the co-existence approach to inferring paleoclimate based on co-occurring taxa (4). We combine this with the current IUCN mammal database to estimate total nutrient diffusion capacity and how that has changed since the extinctions. This methodology ignores barriers

such as deserts, mountains and major rivers and therefore may overestimate transport kinetics in continental interiors. We use equation 1 to estimate diffusion capacity (completely described below) based on mass (M) and the scaling parameters of day range (DD), metabolic rate (MR), population density (PD) and food passage time (PR) (this differs slightly from our previous formulation by excluding parameters not dependent on animal mass).

#### *Marine mammal lateral nutrient distribution*

To calculate nutrient movement in oceans we took two approaches, one for lateral distribution capacity, and one for vertical movement of nutrients. For lateral nutrient distribution, we created a table of estimated changes in regional populations (North Atlantic, North Pacific, and Southern Ocean) of all great whales prior to widespread hunting and post widespread hunting (SI Appendix Table 3). To estimate range, we used the datasets at the website <http://seamap.env.duke.edu/> that gives data on all recorded sightings of whales as well as the IUCN species range database. For 80% of estimated populations, we divided each sighting by total estimated regional population to estimate population per pixel for each species. The remaining 20% were evenly divided in the IUCN species ranges in pixels where there were no recorded sightings in the seamap database. We then were able to estimate a per pixel pre-and post-hunting population density. We also used modified range maps of grey whales (*Eschrichtius robustus*) because it has been extirpated from large regions, with grey whales formerly occurring in the Atlantic (5). We then used scaling theory to estimate mean gut length and mean day range again based on the mean species size. There are much less data on scaling patterns with size among marine mammals than with terrestrial mammals, but evidence suggests size-related trends of some of the largest marine mammals are consistent with scaling trends of terrestrial mammals (6). Recent work shows marine mammals home ranges scale with mass, but with a higher exponent than terrestrial mammals (7). Therefore,

we use similar scaling theory for marine mammals to terrestrial mammals but recognize that this aspect of our work will need modification in the future when more scaling data become available for marine mammals.

### *Formulation of equation 1*

We estimate how land mammals and great whales may diffuse nutrients away from hotspots. We use a diffusion equation calculated previously based on mathematics and data from Doughty et al 2013 and Wolf et al. 2013 (1, 2) with the mathematics repeated below. It is based on a “random walk” model, which is a widely used methodology for simulating animal movement (8-11). Individual animals do not move randomly, but the net movement of all animals over long time periods (>1000 years) begins to approximate random motion. There is a large literature describing how different animal species overlap in space by consuming different foods and moving and sleeping in different patterns to avoid a variety of predators (12-14). Internal demographics of animal groups will also change which will lead to shifting ranges and boundaries of the group over time (15). Below, we show how we can calculate long term movement of nutrients by all animals in an ecosystem over long periods of time if the idea of approximate random motion of animals of all animals in an ecosystem over long periods of time is correct.

In diffusion, the flux is inversely proportional to the local concentration difference in material, with a constant of proportionality termed the “diffusivity”  $D$  (length<sup>2</sup>/time). The equation that best incorporates the diffusive properties of animals is the following reaction diffusion equation:

$$\text{SI-Eq. 1} \quad \frac{dP}{dt} = D * \frac{\partial^2 P}{\partial x^2} - KP + G$$

where  $K$  is a first order loss rate and  $G$  is a gain rate. The diffusivity term  $D$  is based on the “random walk” whose form is demonstrated in the next sections.

### *Random walk*

To calculate a diffusion term we estimate D based on the random walk with the form:

SI-Eq. 2 
$$D = \frac{(\Delta x)^2}{2\Delta t}$$

Where  $\Delta x$  is a change in distance and  $\Delta t$  is a timestep of duration t. In general, a diffusivity can be derived from a random walk (9-11).

#### *Estimate of $D_{\text{excreta}}$*

Nutrients can be moved by animals through either their dung or flesh. Nutrients moved in dung will have different distance and time scales than those moved in the flesh. We therefore calculate D for each separately. Below we start with D for dung.

$\Delta x$  is the daily displacement or day range (DD) of a single animal (DD; km), and  $\Delta t$  is a day. The length scale for diffusivity of ingestion and excretion is the day range multiplied by the average gut passage time (PT; fractions of a day). The time scale is again the food passage time (PT). Therefore, putting this in the framework of the random walk, we estimate that the diffusivity for transport of its dung is  $D_{\text{excreta}} \approx (DD \cdot PT)^2 / (2 \cdot PT)$ , where the numerator is in  $\text{km}^2$  and the denominator is in days.

#### *Estimate of $D_{\text{body}}$*

Next, we calculate a D term for nutrients incorporated into the animal's body. The diffusivity for nutrients in an animal's body mass,  $D_{\text{bones}}$ , is related to the lifetime of the animal L (days) and the residence time of these nutrients is L. The length scale is the home range (HR;  $\text{km}^2$ ). The mean displacement over the lifetime of an animal is related to the range length (RL) and approximately  $HR^{0.5}/2\pi$ . Therefore, if HR is the range used

throughout an animal's lifetime, then  $D_{\text{body}} \approx RL^2/2L$  or  $HR/(8\pi^2L)$ , where the numerator is in  $\text{km}^2$  and the denominator is in days.

### *Consumption of nutrients*

Next, we need to estimate the amount of food and nutrients consumed by a population of animals per area.  $P(x,t)$  is the mass ( $\text{kgP km}^{-2}$ ) of a nutrient. The mass of P at position x at time  $t+\Delta t$  is given by:

$$\text{SI-Eq. 3} \quad P(x, t + \Delta t) = P(x, t) - \text{losses} + \text{gains}$$

The *losses* term is represented in Equation 9 by  $\alpha p(x,t)$ , the fraction of animals leaving x at time t. The loss of a nutrient in dry matter consumed and transported by a population of animals is

$$\text{SI-Eq. 4} \quad \alpha \frac{\text{animals}}{\text{km}^2} * \frac{\text{kg} \frac{DM}{\Delta t}}{\text{animal}} * \frac{\text{kgP}}{\text{kgDM}}(x,t) \Delta t = \alpha PD * MR * [P](x,t) \Delta t = \alpha Q[P](x,t) \Delta t$$

The loss rate of P ( $\text{kg DM km}^{-2}$ ) is the population density of animals (PD;  $\#/\text{km}^2$ ) consuming dry matter (DM) to fulfil their metabolic requirements (MR;  $\text{kg DM/animal/day}$ ). The product of PD and MR is the population consumption rate of DM (denoted Q here), such that  $Q\Delta t$  is the mass of DM consumed in  $\Delta t$  ( $\text{kg DM km}^{-2}$ ). The consumption of the nutrient itself is then determined by  $Q[P](x,t)$ , which has units  $\text{kg P km}^{-2}$ , equivalent to P, the numerator on the left. Gains from adjacent regions will be represented as  $Q[P](x+\Delta x, t)$  and  $Q[P](x-\Delta x, t)$ . A fraction  $\epsilon$  of the consumed nutrient is incorporated into body mass, while the rest  $(1-\epsilon)$  is excreted.

We estimate  $\varepsilon$  as 22.4% for megafauna based on the gross food assimilation efficiency of elephants (16). Incorporation of phosphorus into the body is, of course, more complicated with relative P fraction of biomass increasing with size due to the greater investment in bone growth in larger vertebrates (17). It also changes with animal age as full grown adult vertebrates need less P than immature growing animals. However, since we account for both the fraction in the biomass and the fraction excreted and there are no fates of the nutrient other than body mass or excrement, we use the simple value of 22.4%.

Consider the budget of just the fraction  $(1-\varepsilon)$  of consumed nutrient that will be excreted:

SI-Eq. 5

$$P(x, t + \Delta t) = P(x, t) - (1 - \varepsilon) [\alpha Q[P](x, t) + \frac{\alpha}{2} Q[P](x + \Delta x, t) + \frac{\alpha}{2} Q[P](x - \Delta x, t)]$$

We arrive at the equation:

$$\text{SI-Eq. 6} \quad \frac{dP}{dt} = (1 - \varepsilon) Q D_{\text{excreta}} \frac{\partial^2 [P]}{\partial x^2}$$

Adding in the fraction of nutrient incorporated into body mass we get the complete budget equation:

$$\text{SI-Eq. 7} \quad \frac{dP}{dt} = (1 - \varepsilon) Q D_{\text{excreta}} \frac{\partial^2 [P]}{\partial x^2} + \varepsilon Q D_{\text{excreta}} \frac{\partial^2 [P]}{\partial x^2}$$

The state variable on the left and the right are not the same; P is per area and [P] is per kg DM. Let B be total plant biomass (kg DM km<sup>-2</sup>) such that [P]B=P. We note that B has the same units as Q. Dividing both sides by B:

$$\text{SI-Eq. 8} \quad \frac{\delta [P]}{\delta t} = (1 - \varepsilon) \frac{Q}{B} D_{\text{excreta}} \frac{\partial^2 [P]}{\partial x^2} + \varepsilon \frac{Q}{B} D_{\text{body}} \frac{\partial^2 [P]}{\partial x^2}$$

B represents total plant biomass but animal consumption is only from edible parts of that biomass. Therefore  $B' = \alpha B$ , where  $\alpha$  is the edible fraction of total biomass. We assume for simplicity here that all P made available is taken up, on a fast timescale and used in edible parts. We may revisit this assumption in future work. If these fractions can be assumed equal, then:

$$\text{SI-Eq. 9} \quad \frac{\delta[P]}{\delta t} = (1 - \varepsilon) \frac{Q}{\alpha B} D_{\text{excreta}} \frac{\partial^2[P]}{\partial x^2} + \varepsilon \frac{Q}{\alpha B} D_{\text{body}} \frac{\partial^2[P]}{\partial x^2}$$

If  $Q/B$  can be assumed constant, then:

$$\text{SI-Eq. 10} \quad \frac{dP}{dt} = \Phi_{\text{excreta}} \frac{\partial^2 P}{\partial x^2} + \Phi_{\text{body}} \frac{\partial^2 P}{\partial x^2}$$

where the  $[P]$  terms on both sides have been multiplied by  $\alpha B$ , and

$$\text{SI-Eq. 11} \quad \Phi_{\text{excreta}} = (1 - \varepsilon) \frac{Q}{\alpha B} D = (1 - \varepsilon) \frac{PD}{\alpha B} * MR * \frac{(DD * PR)^2}{2 * PR}$$

$$\text{SI-Eq. 12} \quad \Phi_{\text{body}} = \varepsilon \frac{Q}{\alpha B} D = \varepsilon \frac{PD}{\alpha B} * MR * \frac{HR}{8\pi^2 L}$$

We solve the equations above using datasets and methods described in previous work(2). We estimated  $\Phi$  as a function of  $M$  in two ways: first, we calculated the allometries for each term as a function of  $M$  (using ordinary least squares) and combined the resulting coefficients to yield an allometric equation for  $\Phi$  that results from scaling arguments (see Wolf et al. 2013 for the allometries). In our previous work we find  $\Phi_{\text{body}}$  to be several orders of magnitude smaller than  $\Phi_{\text{excreta}}$  and we therefore remove  $\Phi_{\text{body}}$  from our formulation and in  $\Phi$  in equation 1 refers to only  $\Phi_{\text{excreta}}$ . In equation 1, we remove the  $\alpha B$  and  $\varepsilon$  term as it is not based on animal mass. Based on our datasets we calculate the below value of  $\Phi$  which we use as equation 1 in the text and which was originally formulated in Table 1 of Wolf et al. 2013.



SI-Eq. 13

$$\Phi = MR * PD * \frac{(DD * PR)^2}{2 * PR} = 0.78 * 0.05 * M^{1.17}$$

## *II - Calculation of vertical nutrient movement by marine mammals and sea to land nutrient fluxes by seabirds and anadromous fish*

### *Marine mammal vertical nutrient distribution*

To calculate vertical nutrient movement, we created a table of diving marine mammals and regional population estimates (North Atlantic, North Pacific, and Southern Ocean) prior to widespread hunting and post widespread hunting (SI Appendix Table 4). We calculate this vertical distribution of nutrients for nine marine mammals whose common dive depths are greater than 100 meters ((18), SI Appendix Table 4). This proportion would hold for other important limiting nutrients, such as N and Fe. To estimate range, we used the IUCN species range dataset for all diving marine mammals except for great whales (*Balaenoptera physalus* and *Physeter microcephalus*), which we again use the seimap dataset (<http://seimap.env.duke.edu/>). We divided regional population estimates by species range to estimate population density per pixel for each species and used equation 14 to estimate food consumption (dry matter: DM) based on mean species mass (2).

$$\text{Kg DM/\#/day} = 0.021 \times M^{0.716} \quad \text{SI-Eq. 14}$$

Based on these consumption patterns, an average ocean redfield ratio of Carbon: Phosphorus = 106:1 (but since most marine mammals are predators and higher tropic levels such as krill have a ratio closer to 50:1(19), we use 50:1), and defecation rate of 80% (20, 21), we estimate movement of P from depth to the surface ocean. We compare this to P concentrations found at depth and at the surface from the Ocean Climate Laboratory/National Oceanographic Data Center/NESDIS/NOAA/U.S. <http://rda.ucar.edu/datasets/ds254.0/>

### *Nutrient distribution by seabirds*

We use seabird species ranges for either year-round residents or breeding seasons from birdlife.org (22) and their estimated body masses based on Dunning et al. 2007 and Dunning – unpublished data (23) to estimate total global seabird consumption. To estimate metabolic consumption as a function of mass we use equation 14 and to estimate density as a function of mass we use Juanes et al. (1986) which found a strongly significant ( $P < 0.001$ ,  $r^2 = 0.27$ ,  $N = 461$ ) relationship for carnivorous birds (24):

$$\text{ind/km}^{-2} = 10^{(2.18 + \log_{10}(M) \cdot -0.67)} \quad \text{SI-Eq. 15}$$

We use all species of seabirds (223 species) from the following families: Spheniscidae, Diomedidae, Procellariidae, Pelacanoididae, Hydrobatidae, Pelecanidae, Sulidae, Phalacrocoracidae, Fregatidae, Phaethontidae, Stercorariidae, Laridae, Sternidae, Rhynchopidae, Alcidae (22). We estimate phosphorus in food supply using a redfield ratio of C:P = 106:1 (19).

Seabird guano deposition on land is difficult to calculate because of the uncertainty of the percentage guano arriving on land versus being defecated in the sea. To roughly estimate percentage of nutrients that arrive on land, we use data from a detailed study of nutrient distribution on seven bird islands (Anderson and Polis 1999) as well as a larger seabird dataset from Mulder et al 2011 as a case study to calibrate our larger model (25, 26). A recent review (26) of guano deposition on seabird islands showed that due to its aridity, the P concentrations were unusually high in the island studied by Anderson and Polis (1999). However, below we are able to account for the aridity using a P model (see equations 14-16 below) and we focus on the group of islands described in Anderson and Polis (1999). These seven bird islands had a combined area of about  $1 \text{ km}^2$  ( $0.86 \text{ km}^2$ ), and on these islands P increased in the soil from  $0.35 \pm 0.17\%$  P on the non-bird islands to  $1.30 \pm 0.24\%$  P on the

bird islands. In vegetation, the P increased from  $0.16 \text{ g m}^{-2}$  in three plant types (Atriplex, Opuntia, and annuals) to  $0.41 \text{ g m}^{-2}$ , an increase of 250%.  $\delta^{15}\text{N}$  stable isotope data verified that the increased fertility was almost certainly due to the seabird nesting.

We use mass scaling relationships to calculate consumption by the seabirds in this study. Seabird foraging radius scales with mass (27) as does bird gut length and food retention time (28) and scaling theory has generally been applicable to seabirds (29). We estimate total consumption rates for the species of seabirds living in the identified Gulf of California islands. To estimate a mean percentage of guano transferred from sea to land we calculated (using equations 14 and 15) that the 23 seabird species in the region of the seven Gulf of California islands from (25) consume  $12 \text{ kg km}^{-2}$ , or  $\sim 0.1 \text{ kg of P km}^{-2}$ . Mass-based scaling of seabird foraging area suggests that the birds nesting on these seven islands have a mean foraging radius of 326km, or about half of the Gulf of California,  $80,000 \text{ km}^2$  (27). We justify this by estimating seabird foraging radius of the seabird species based on mass (27) and we estimate that foraging radius is  $286 \text{ km} + 61 * M$ . Therefore,  $8,000 \text{ kg P yr}^{-1}$  was consumed by these nesting birds and an unknown amount of this was deposited on all the islands with a total area of  $\sim 1 \text{ km}^2$ . On these islands, total soil P increased by  $\sim 1\%$ , which is  $\sim 1 \text{e}6 \text{ kg of P km}^{-2}$  (25). We can roughly estimate the quantity of P needed to increase P in  $\sim 100 \text{ kg of soil}$  (in a  $1 \text{ m}^2$  area assuming the top 10cm of soil, a soil density of  $1.2 \text{ g cm}^{-3}$ ) by  $1\%$  as  $\sim 1 \text{ kg}$ . To achieve this steady state concentration of P and assuming a loss rate of  $0.0014 \text{ yr}^{-1}$  (30) (see below for calculation of the loss rate), then a flux of  $1400 \text{ kg P km}^{-2} \text{ yr}^{-1}$  must be added yearly to the soil or  $\sim 18\%$  of the  $8,000 \text{ kg P}$  per year that was consumed. Therefore, as a rough proxy, we assume 20% of the seabird P will arrive on land. As this is clearly a highly uncertain figure, in a sensitivity analysis, we varied this percentage between 5 to 50%.

We calculate the loss rate based on a P model of  $0.0014 \text{ yr}^{-1}$  (30). We estimate P losses from the system based on the following equations from (30):

$$\text{SI-Eq. 14} \quad LQ(s) = k_l s^c$$

$$\text{SI-Eq. 15} \quad L_o = (k_r * LQ(s) + k_f) * P_o$$

$$\text{SI-Eq. 16} \quad L_d = LQ(s) * \frac{P_d}{n * Zr * s}$$

where  $s$  is the yearly averaged soil moisture (dimensionless);  $c$  is 3;  $k_l$  is runoff or leakage at saturation, which is  $0.1 \text{ (yr}^{-1}\text{)}$ ;  $k_r$  is the losses regulation rate  $0.002 \text{ (yr}^{-1}\text{)}$ ;  $P_o$  is organic P;  $P_d$  is the dissolved P;  $Zr$  is soil depth (1m);  $n$  is soil porosity (0.4);  $L_o$  is the loss rate of  $P_o$ ; and  $L_d$  is the loss rate of  $P_d$ .  $k_f$ , or a loss rate from ice, wind, humans, or fire, is  $0.00005$ . We estimate the steady state ratios of  $P_o$  to  $P_d$  following figure 2 in Buendia et al. 2010(30).

### *Nutrient movement by anadromous fish*

To estimate anadromous fish nutrient movement from the sea to land on a global basis, we first compile a list of likely anadromous fish species (110 species and an additional 10 possibilities listed as maybe) from (31) shown in column 1 of SI Appendix table 5(32). We then searched the IUCN database (<http://www.iucnredlist.org/technical-documents/spatial-data>) for species maps. We found maps for 42 species. We substituted a similar species within the same genus for 47 species (column 2 of SI Appendix table 5). Thirty-three species, for which there were no data for any species within the genus, were left blank.

To estimate historical population densities of such fish, we used a range of studies. Populations of anadromous fish have declined to less than 10% of their historical numbers in the Pacific Northwest (33), the Netherlands (34), and the North Atlantic (35). In the North Atlantic, the relative abundances of 13 of 24 species had dropped to less than 2% of historic levels; abundances had dropped to less than 10% in the others. There were also large declines in the anadromous sea lampreys (36) and sturgeons (37). In regions where anadromous fish populations were measured, population reductions from historic highs in global populations were similar to those found in the Pacific Northwest of the USA, where data was particularly strong. Gresh et al. (2000) estimated movement of P for both historical and modern populations for the entire Columbia river basin, Oregon coast, Washington coast, Puget sound, and California (33).

For each region, we calculated the P moved for each species on a per area basis. Because the Gresh et al. study provided the strongest regional level data of P movement, we then applied this for each species globally to get an estimate of nutrient movement by anadromous fish. We do not have good data for mean body mass for most species. These

species are clearly a wide range of sizes. However, size and population density often vary inversely. On average, it is a reasonable assumption that animal biomass per species per area is relatively constant. The theoretical explanation for this phenomena is termed the “law of energy equivalence”, which argues that the population-level biomass should be equal across a range of animal sizes (38). Therefore, for species in which mass is unknown, we estimate that fish biomass per unit area, which should, to first order, be a function of the total number of species present. In recognition of the high uncertainty in this estimate, we vary several terms in our analysis by up to 200% in a sensitivity study (SI Appendix Table 1 and 2).

### *Sensitivity analysis*

There are large uncertainties in many of the spatial maps, scaling coefficients, and assumptions used in our analysis. We have attempted to quantify this uncertainty in a sensitivity study where we calculate an estimated global flux of P based on the low and high uncertainty value. In table one, we describe the variable and the largest source of its uncertainty. In table two, we quantify this uncertainty, explain how we quantified the uncertainty, and show the results of how our final values could change based on both the low and high estimated values.



### *Impact of predation on our results*

Many ecosystems have lost predators at higher rates than herbivores. How might the absence of predators affect nutrient transfer by herbivores? Human-induced loss of predators may enable mid-sized herbivores to reach unnaturally high densities, for example, in deer populations (39). However, in many parts of the world human hunting has replaced natural predator hunting, thus keeping modern herbivore populations down. If certain mid-sized herbivores were more abundant, how might this affect nutrient movement? Megaherbivores (> 1000kgs) are unique because their large size makes them less susceptible to predation, like predator-free populations of deer today, and they would have existed in high population densities. However, the large size of megaherbivores (> 1000kgs) would have made them more important than mid-sized herbivores for the transport of nutrients (1, 2). Therefore, in the past, there would have been abundant megafauna and predation limited mid-sized herbivores. Today this situation has been replaced by a community without megafauna but with potentially more abundant but less diverse mid-sized herbivores, but with more restricted movement.

**Table 1** – Description of the variables modified in the sensitivity analysis and a description of what the uncertainty is.

<b>Variable</b>	<b>Description</b>	<b>Uncertainty</b>	<b>reference</b>
<b>Megafauna range maps</b>	Predicting the spatial regions where the now extinct megafauna had lived	Predicting ranges of extinct animals is difficult due to taphonomic bias. Using the range maps from Faurby and Svenning (40), there is a correlation between predicted and historic ranges of 0.856 for 39 species in North America. Since the historic ranges are not known with certainty and since the precision in these 39 species are not guaranteed to be representative of the entire megafauna set, we used an uncertainty of double this (+/- 30%)	(40)
<b>Animal body mass</b>	The estimated mean body mass of a species	The uncertainty of individual species are generally captured with +/-25. However, we use an error of +/- 10% which is for entire communities because as long as the estimates are unbiased the combined error for all co-occurring species will be smaller since some are under and some are over estimated.	
<b>Phi coefficient</b>	This is the nutrient diffusion coefficient from equation 1 previously calculated in Doughty et al. and Wolf et al. (2013).	This coefficient is based on 17 species. However, larger datasets with some values missing show similar values. An estimate for just large animals (>44kg) estimated a larger coefficient (1.45).	(1, 2)
<b>Assumption of random motion</b>	For mathematical expediency, we use a random walk model when averaging for all animals in an ecosystem over long periods of time.	This is a well-tested model used in hundreds of papers. Simulations over shorter time periods can be done numerically on regional scales to test the assumption.	(9-11)
<b>Whale historical population density</b>	Estimates of historic populations of great whales	There is great uncertainty in past global population densities of great whales prior to human hunting.	See table 3 and 4
<b>Whale range maps</b>	We used a combination of the IUCN databases plus whale sighting records	IUCN map are very broad and do not account for regions with greater or fewer populations. We correct for this by using whale sighting data. This is probably biased towards regions more populated by people	(32, 41)
<b>Whale lateral</b>	The estimated distance moved between whale	Due to data limitations, the coefficient is based on all	(2, 6, 7)

<b>diffusion coefficient</b>	food consumption and defecation based on mean body size.	mammal data and is not specific to whales. This is likely a large underestimate, since (7) showed space use for whales had a much higher exponent than for terrestrial mammals.	
<b>Vertical movement of nutrients by marine mammals</b>	Estimate of nutrients moved by deep diving animals to the surface waters	This term is dependent on estimating population densities, metabolic rates, and the ratio of food consumed at depth and defecated in surface waters.	(2)
<b>Seabird range maps</b>	Estimate of number and spatial area of each seabird species	IUCN species range maps for seabirds are likely accurate over land regions, but much less accurate over ocean regions.	(22)
<b>Seabird food consumption</b>	Estimate of metabolic consumption and population density based on mass scaling laws.	These are based on scaling coefficients and are likely within the 95% confidence interval of the calculated slope.	(2, 24)
<b>Guano deposition on land</b>	Estimating the percentage of seabird guano that arrives on land.	Much guano is defecated at sea versus deposited at nesting sites. The percentage likely varies widely for each species. However, we estimate this based on data from (25, 26).	(25, 26)
<b>Anadromous fish abundance</b>	Which fish species are anadromous? Where do they live? What were there historical population numbers?	The best reference on this (31) details 110 anadromous fish species, along with 10 other possible ones. This likely underestimates the total number of anadromous fish species because it is difficult to estimate. We do not have species range maps for all of these species and this is another likely source of underestimation. There is little data on historical abundances outside of N. America and Europe. We assume historical abundances everywhere were similar to N. America and Europe.	(31, 32)
<b>Anadromous fish nutrient movement</b>	We use estimates of regional P movement by all anadromous fish in the Pacific Northwest of the US from Gresh et al. 2000. This paper quantifies historical population densities and P contained within these bodies.	We have no data on mean species size and there is no data on historical population estimates outside of N. America and Europe.	(33)



**Table 2** – Values used in our sensitivity analysis: the estimated range in uncertainty, how this uncertainty was assessed, and a global calculation of the P flux for the low and high estimates. Expert opinion was estimated by a group of experts (the authors of the paper) of the variable value in which the group was 95% certain the true value would fall within. If the number is calculated as a slope, then the 95% confidence interval ( $1.96 \times \text{standard error on the slope}$ ) is the potential error.

<b>variable</b>	<b>Value used</b>	<b>Potential error estimate</b>	<b>How the error was assessed</b>	<b>Past Global P flux</b>	<b>Current Global P flux</b>	<b>reference</b>
<b>Megafauna range maps</b>	See figure 1	$\pm 30\%$ for megafauna $\pm 10\%$ for current animals	Expert opinion	$13\text{-}23\text{e}4 \text{ km}^2 \text{ yr}^{-1}$	$1.1\text{-}2.1\text{e}4 \text{ km}^2 \text{ yr}^{-1}$	(40)
<b>Animal body mass</b>	See (40, 42)	$\pm 10\%$	Expert opinion	$16\text{-}20\text{e}4 \text{ km}^2 \text{ yr}^{-1}$	$1.4\text{-}1.9\text{e}4 \text{ km}^2 \text{ yr}^{-1}$	(40, 42)
<b>Phi coefficient</b>	1.17	$\pm 0.24$	Slope error	$3\text{-}130\text{e}4 \text{ km}^2 \text{ yr}^{-1}$	$0.4\text{-}10\text{e}4 \text{ km}^2 \text{ yr}^{-1}$	(2)
<b>Assumption of random motion</b>	Random walk model	Run model numerically	Computer simulation	Simulations available upon request.	Simulations available upon request.	(9-11)
<b>Whale population density</b>	See table 4	$\pm 50\%$ historical $\pm 20\%$ current	Expert opinion	$170\text{-}510 \text{ million kg yr}^{-1}$	$64\text{-}96 \text{ million kg yr}^{-1}$	See table 3 and 4
<b>Whale range maps</b>	See figure 2	$\pm 30\%$ historical $\pm 10\%$ current	Expert opinion	$240\text{-}310 \text{ million kg yr}^{-1}$	$70\text{-}90 \text{ million kg yr}^{-1}$	(32, 41)
<b>Whale lateral diffusion coefficient</b>	Eq. 1	$+30\%$ $-10\%$	Slope error and expert opinion	$5.7 - 8.3\text{e}5 \text{ km}^2 \text{ yr}^{-1}$	$2.9\text{-}4.2 \text{e}4 \text{ km}^2 \text{ yr}^{-1}$	(2, 6, 7)
<b>Vertical movement of nutrients by marine mammals</b>	Eq. 2 and 80% of food consumed at depth moved vertically	Eq. 2 - $\pm 0.04$ 65-95%	Slope error and expert opinion	$260\text{-}430 \text{ million kg yr}^{-1}$	$54\text{-}110 \text{ million kg yr}^{-1}$	(2)
<b>Seabird range maps</b>	See Figure 3	$\pm 20\%$	Expert opinion	$5\text{-}7.6 \text{ million kg yr}^{-1}$	NA	(22)
<b>Seabird food consumption</b>	Eq. 2 and 3	Eq. 2 - $\pm 0.04$	Slope error	$3\text{-}9 \text{ million kg yr}^{-1}$	NA	(2, 24)

Eq. 3 - ±0.10						
<b>Guano deposition on land</b>	20%	5-50%	Slope error and expert opinion	1.5-16 million kg yr <sup>-1</sup>	NA	(25, 26)
<b>Anadromous fish abundance</b>	See figure 3	+200% -50%	Slope error and expert opinion	71-430 million kg yr <sup>-1</sup>	3-16 million kg yr <sup>-1</sup>	(31, 32)
<b>Anadromous fish nutrient movement</b>	Scaling results from Gresh et al. 2000	+100% -50%	Expert opinion	71-280 million kg yr <sup>-1</sup>	3-12 million kg yr <sup>-1</sup>	(33)

**Table 3** – Data table used to calculate lateral nutrient distribution capacity of great whales in oceans. Numbers are in thousands. NA is the North Atlantic, NP is the North Pacific, SH is the Southern Ocean. Unless otherwise stated all data references are from Christensen 2006 (43). Estimating past populations of animals has inherent large uncertainties due to poor historical data. Numbers with especially high uncertainty are listed as a range with a footnote below explaining the possible discrepancy from Christensen 2006 (43). Due to the large uncertainty in these numbers, in a sensitivity study, we estimate the uncertainty of our estimates at 30% (SI appendix Table 2).

Species	Pre NA	Pre NP	Pre SH	Pre Other	2001 NA	2001 NP	2001 SH	2001 Other	Reference
<i>Balaenoptera borealis</i>	10.6	68.4	167	0	7	14.7	27.4	0	Global populations from (44)
<i>Physeter macrocephalus</i>	0	0	0	1110	0	0	0	360	
<i>Balaenoptera physalus</i>	73	65	625	0	56	31	23	0	
<i>Eschrichtius robustus</i>	0	25	0	0	0	16	0	0	
<i>Balaenoptera musculus</i>	7.5	6	256-327 <sup>*1</sup>	0	0.4	3	1-3 <sup>*2</sup>	0	
<i>Balaenoptera brydei</i>	0	52	94	0	0	41	91	0	Christensen and IUCN Red List
<i>Megaptera novaeangliae</i>	112	20	140-199 <sup>*3</sup>	0	20	20	22.5-40 <sup>*4</sup>	0	Estimates for pre-NA from (45); estimates for contemporary humpbacks in NP from (46), pre NP #s have been rounded up to reflect this increase
<i>Balaenoptera acutorostrata</i>	211	47	379	0	157	32	318	0	
<i>Balaenoptera</i>	211	47	379	0	157	32	318	0	

<i>bonaerensis</i>								
<i>Eubalaena glacialis</i>	14	0	0	0	0.4	0	0	0
<i>Eubalaena australis</i>	0	0	70-86 <sup>*5</sup>	0	0	0	10-12 <sup>*6</sup>	0
<i>Eubalaena japonica</i>	0	31.75	0	0	0	0.4	0	0
<i>Balaena mysticetus</i>	0	0	0	89	0	0	0	9

(47)

<sup>\*3</sup>Estimated population for Antarctic blue whales could be 256,000.

<sup>\*4</sup>For Antarctic blue whales in 1997 the population was 2,300 individuals. If one projects that to 2001 given the estimated growth rate for this population (6.4%/year as agreed by the IWC), one gets an abundance of 3,000.

<sup>\*3</sup>In the Southern Hemisphere, Humpback whales estimated pre-exploitation abundance (K) is 140,000 given the IWC most recent assessments.

<sup>\*4</sup>The most recent abundance estimate for all whales combined is 80,000 in 2010. It is hard to extrapolate back to 2001 (which is the year shown in the table), but a crude calculation indicates the 2001 abundance would have been at least 40,000 whales.

<sup>\*5</sup>The IWC estimated populations at about 70,000 whales under the assumption of an intrinsic growth rate of 7%/year (which is consistent with the three major right whale breeding populations).

<sup>\*6</sup>The abundance of Southern Right Whales in 2001 projected from the IWC assessments is 10,000.



**Table 4 – Data table used to calculate vertical nutrient distribution by marine mammals. Dive depths are from Ponganis 2011 (18). Population sizes are from Christensen 2006 (43) unless otherwise stated.**

Species	Pre NA	Pre NP	Pre SH	Pre Other	2001 NA	2001 NP	2001 SH	2001 Other	weight	Diving depth	reference
<i>Cystophora cristata</i>	700	0	0	0	70	0	0	0	200	100- 600	IUCN Red List
<i>Globicephala macrorhynchus</i>	33	624	0	0	33	624	0	0	2000	100- 800	IUCN Red List
<i>Hyperoodon ampullatus</i>	58	0	0	0	49	0	0	0	6500	800	
<i>Globicephala melas</i>	871	0	0	0	795	0	0	0	2500	100- 800	
									400		Pre hunting estimates are based on range reduction
<i>Phocarcots hookeri</i>	0	0	120	0	0	0	12	0		NaN	
<i>Mirounga angustirostris</i>	0	200	0	0	0	200	0	0	2000	437	
<i>Mirounga leonine</i>	0	0	1000	0	0	0	650	0	2000	269- 552	Iucn Red List
<i>Physeter microcephalus</i>	0	0	0	1110	0	0	0	360	14000	400- 900	Global populations from (44)
<i>Balaenoptera physalus</i>	7.5	6	327	0	0.4	3	1	0	150000	180- 200	
<i>Ziphius cavirostris</i>	0	97	0	100	0	97	0	100	2500	1070- 1334	
<i>Leptonychotes</i>	0	0	500	0	0	0	500	0	500	150-	

<i>weddelli</i>	400
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**Table 5 – Species list of anadromous fish from(31), species used in our estimates (if no species range map was available, we used a similar species from the same genus), the status is the certainty of if the fish were anadromous (maybe is not certain, and blank is more certain), and the estimated pixel area (in km<sup>2</sup>) occupied by the species which includes both the land and river area within the pixel.**

<b>Anadromous fish</b>	<b>species used</b>	<b>status</b>	<b>estimated area (km<sup>2</sup>)</b>
<i>Acipenser baerii</i>	<i>Acipenser baerii</i>		1.01E+05
<i>Acipenser brevirostrum</i>	<i>Acipenser brevirostrum</i>		9.06E+05
<i>Acipenser fulvescens</i>	<i>Acipenser fulvescens</i>	maybe	5.61E+06
<i>Acipenser gueldenstaedtii</i>	<i>Acipenser gueldenstaedtii</i>	maybe	3.41E+06
<i>Acipenser medirostris</i>	<i>Acipenser medirostris</i>		6.01E+05
<i>Acipenser nudiiventris</i>	<i>Acipenser nudiiventris</i>	maybe	2.04E+06
<i>Acipenser oxyrinchus</i>	<i>Acipenser oxyrinchus</i>		2.45E+06
<i>Acipenser ruthenus</i>	<i>Acipenser ruthenus</i>		4.17E+06
<i>Acipenser stellatus</i>	<i>Acipenser stellatus</i>		3.48E+06
<i>Acipenser sturio</i>	<i>Acipenser sturio</i>		4.26E+06
<i>Acipenser transmontanus</i>	<i>Acipenser transmontanus</i>	maybe	1.21E+06
<i>Acipenser usohuso</i>	NaN		0.00E+00

<i>Alosa aestivalis</i>	<i>Alosa aestivalis</i>	1.02E+06
<i>Alosa alabamae</i>	<i>Alosa alabamae</i>	8.97E+05
<i>Alosa caspia</i>	<i>Alosa caspia</i>	1.07E+06
<i>Alosa chrysochloris</i>	<i>Alosa tanaica</i>	2.94E+05
<i>Alosa fallax</i>	<i>Alosa fallax</i>	2.99E+06
<i>Alosa kessleri</i>	<i>Alosa kessleri</i>	1.15E+06
<i>Alosa mediocris</i>	<i>Alosa mediocris</i>	6.88E+05
<i>Alosa pontica</i>	<i>Alosa volgensis</i>	8.39E+05
<i>Alosa pseudoharengus</i>	<i>Alosa pseudoharengus</i>	2.25E+06
<i>Alosa sapidissima</i>	<i>Alosa sapidissima</i>	1.97E+06
<i>Anchoviella lepidentostole</i>	NaN	0.00E+00
<i>Anodontostoma chacunda</i>	NaN	0.00E+00
<i>Arius felis</i>	<i>Arius arius</i>	1.94E+06
<i>Arius heudeloti</i>	<i>Arius uncinatus</i>	4.62E+04
<i>Arius militaris</i>	<i>Arius acutirostris</i>	2.59E+05
<i>Arius graeffei</i>	<i>Arius gagora</i>	1.54E+05
<i>Arius latiscutatus</i>	<i>Arius gigas</i>	1.80E+06
<i>Arius madagascariensis</i>	<i>Arius madagascariensis</i>	1.18E+05
<i>Batanga lebretonis</i>	NaN	0.00E+00
<i>Clupanodon thrischacunda</i>	<i>Clupeonella caspia</i>	5.59E+05
<i>Clupeonella cultiventris</i>	<i>Clupeonella caspia</i>	5.59E+05
<i>Coregonus albula</i>	<i>Coregonus albula</i>	2.70E+06
<i>Coregonus artedii</i>	<i>Coregonus alpinus</i> maybe	6.63E+03

<i>Coregonus artedii</i>	<i>Coregonus autumnalis</i>		6.76E+06
<i>Coregonus autumnalis</i>	<i>Coregonus baerii</i>		1.63E+05
<i>Coregonus canadensis</i>	<i>Coregonus lavaretus</i>	maybe	2.01E+04
<i>Coregonus clupeaformis</i>	<i>Coregonus nasus</i>		8.14E+06
<i>Coregonus laurettae</i>	<i>Coregonus oxyrinchus</i>		1.19E+05
<i>Coregonus lavaretus</i>	<i>Coregonus megalops</i>		2.02E+05
<i>Coregonus muskun</i>	<i>Coregonus peled</i>		4.50E+06
<i>Coregonus nasus</i>	<i>Coregonus reighardi</i>		3.09E+05
<i>Coregonus oxyrinchus</i>	<i>Coregonus vandesius</i>	maybe	4.42E+04
<i>Coregonus ussuriensis</i>	<i>Coregonus zenithicus</i>	maybe	1.56E+06
<i>Dormitator latifrons</i>	<i>Dormitator lebretonis</i>		2.53E+06
<i>Dormitator maculatus</i>	NaN		0.00E+00
<i>Dorosoma cepedianum</i>	<i>Dorosoma cepedianum</i>		5.52E+06
<i>Dorosoma petenense</i>	<i>Dorosoma petenense</i>		1.62E+06
<i>Eleotris pisonis</i>	<i>Eleotris oxycephala</i>		2.22E+06
<i>Gasterosteus aculeatus</i>	<i>Gasterosteus aculeatus</i>		9.70E+06
<i>Geotria Australis</i>	<i>Geotria australis</i>		1.82E+06

<i>Hemisalanx prognathus</i>	NaN	maybe	0.00E+00
<i>Herkotslichthys gotoi</i>	NaN		0.00E+00
<i>Herkotslichthys koningsbergeri</i>	NaN		0.00E+00
<i>Hucho perryi</i>	<i>Hucho hucho</i>		3.55E+05
<i>Hypomesus transpacificus</i>	<i>Hypomesus olidus</i>		1.66E+07
<i>Hypomesus olidus</i>	<i>Hypomesus transpacificus</i>		1.06E+05
<i>Ilisha novalcula</i>	<i>Ilisha novacula</i>		8.56E+05
<i>Ilisha africana</i>	NaN		0.00E+00
<i>Ilisha megaloptera</i>	NaN		0.00E+00
<i>Lampetra japonica</i>	<i>Lampetra aepyptera</i>		1.30E+06
<i>Lampetra wagneri</i>	<i>Lampetra hubbsi</i>		2.31E+05
<i>Lampetra tridentata</i>	<i>Lampetra richardsoni</i>		8.01E+05
<i>Lampetra ayresii</i>	<i>Lampetra ayresii</i>		6.69E+05
<i>Lampetra fluviatilis</i>	<i>Lampetra planeri</i>		3.72E+06
<i>Lampetra tridentata</i>	<i>Lampetra ninae</i>		4.22E+04
<i>Lepisosteus osseus</i>	<i>Lepisosteus osseus</i>		4.99E+06

<i>Leucopsarion petersi</i>	NaN		0.00E+00
<i>Lovettia seali</i>	NaN		0.00E+00
<i>Lycengraulis olidus</i>	NaN		0.00E+00
<i>Lycengraulis simulator</i>	NaN		0.00E+00
<i>Microgadus tomcod</i>	<i>Microgadus tomcod</i>		1.68E+05
<i>Microphis brachyurus</i>	<i>Microphis brachyurus</i>		2.35E+05
<i>Mordacia mordax</i>	NaN		0.00E+00
<i>Morone saxatilis</i>	<i>Morone saxatilis</i>		1.63E+06
<i>Morone americanus</i>	<i>Morone americana</i>		1.19E+06
<i>Nematalosa vlaminghi</i>	NaN		0.00E+00
<i>Nematalosa galathea</i>	NaN		0.00E+00
<i>Neosalanx jordani</i>	<i>Neosalanx brevirostris</i>	maybe	2.53E+06
<i>Oncorhynchus gilae</i>	<i>Oncorhynchus gilae</i>	maybe	2.01E+05
<i>Oncorhynchus nerka</i>	<i>Oncorhynchus nerka</i>	maybe	2.62E+06
<i>Oncorhynchus tshawytscha</i>	NaN		0.00E+00
<i>Oncorhynchus keta</i>	NaN		0.00E+00
<i>Oncorhynchus kisutch</i>	NaN		0.00E+00
<i>Oncorhynchus masou</i>	NaN		0.00E+00
<i>Osmerus mordax</i>	<i>Osmerus mordax</i>		4.26E+06
<i>Osmerus eperlanus</i>	<i>Osmerus eperlanus</i>		2.63E+06

<i>Pellona ditcheli</i>	<i>Pellonula vorax</i>		1.83E+06
<i>Pellonula leonensis</i>	NaN		0.00E+00
<i>Pellonula vorax</i>	NaN		0.00E+00
<i>Petromyzon marinus</i>	<i>Petromyzon marinus</i>		4.34E+06
<i>Prosopium cylindraceum</i>	<i>Protosalanx chinensis</i>		1.25E+06
<i>Protosalanx chinensis</i>	NaN		2.17E+07
<i>Protosalanx hyalocranium</i>	NaN	maybe	0.00E+00
<i>Pungitius pungitius</i>	<i>Pungitius pungitius</i>		0.00E+00
<i>Retropinna retropinna</i>	<i>Retropinna retropinna</i>		4.81E+05
<i>Retropinna tasmanica</i>	NaN		0.00E+00
<i>Retropinna semoni</i>	NaN		0.00E+00
<i>Salangichthys microdon</i>	NaN		0.00E+00
<i>Salangichthys ishikawae</i>	NaN		0.00E+00
<i>Salanx ariakensis</i>	<i>Salanx chinensis</i>		4.62E+05
<i>Salanx cuvieri</i>	<i>Salanx cuvieri</i>	maybe	2.65E+05
<i>Salanx acuticeps</i>	NaN	maybe	0.00E+00
<i>Salmo salar</i>	<i>Salmo salar</i>		2.12E+06
<i>Salmo trutta</i>	<i>Salmo trutta</i>		1.01E+07
<i>Salmo gairdneri</i>	<i>Salmo macrostigma</i>		3.68E+05
<i>Salmo clarki</i>	<i>Salmo labrax</i>		2.34E+06
<i>Salmo penshinensis</i>	<i>Salmo platycephalus</i>		5.25E+04



<i>Salvelinus alpinus</i>	<i>Salvelinus alpinus</i>	1.22E+07
<i>Salvelinus fontinalis</i>	<i>Salvelinus umbla</i>	1.71E+05
<i>Salvelinus malma</i>	<i>Salvelinus murta</i>	4.15E+03
<i>Salvelinus leucomaenis</i>	<i>Salvelinus inframundus</i>	6.14E+04
<i>Salvelinus confluentis</i>	<i>Salvelinus confluentus</i>	2.63E+06
<i>Spirinchus lanceolatus</i>	<i>Spirinchus thaleichthys</i>	5.37E+05
<i>Spirinchus thaleichthys</i>	NaN	0.00E+00
<i>Sokellia anisodon</i>	<i>Stokellia anisodon</i>	6.82E+04
<i>Strongylura krefftii</i>	<i>Strongylura marina</i>	1.25E+06
<i>Tenualosa ilisha</i>	<i>Tenualosa ilisha</i>	2.40E+06
<i>Tenualosa macrura</i>	<i>Tenualosa thibaudeaui</i>	2.61E+05
<i>Tenualosa reevesi</i>	NaN	0.00E+00
<i>Tenualosa toli</i>	NaN	0.00E+00

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